

**Ice Surface Temperature Retrieval from AVHRR, ATSR,  
and Passive Microwave Satellite Data:  
Algorithm Development and Application**

NAGW-3437

**SEMI-ANNUAL REPORT, YEAR 2**

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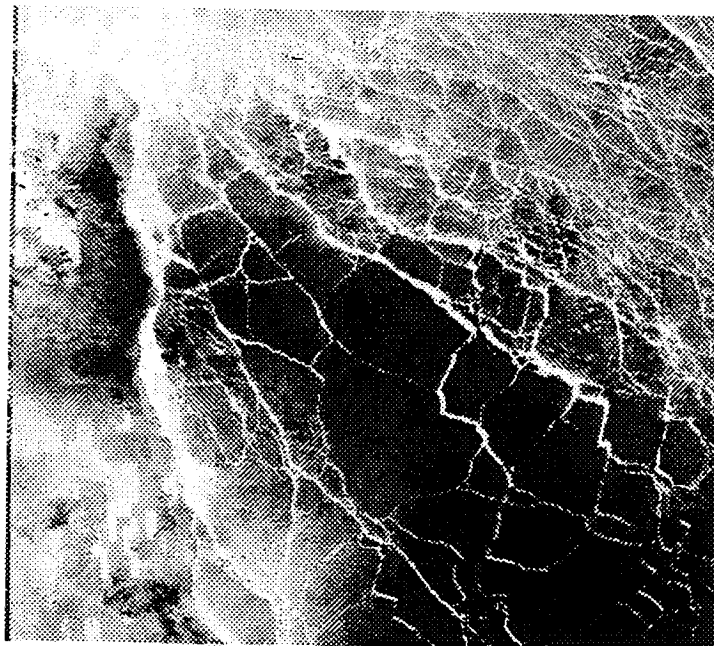
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(NASA-CR-197542) ICE SURFACE  
TEMPERATURE RETRIEVAL FROM AVHRR,  
ATSR, AND PASSIVE MICROWAVE  
SATELLITE DATA: ALGORITHM  
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**ATSR Brightness Temperatures, Beaufort Sea**



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## SUMMARY

During the first half of our second project year we have accomplished the following:

- acquired a new AVHRR data set for the Beaufort Sea area spanning an entire year,
- acquired additional ATSR data for the Arctic and Antarctic now totalling over seven months,
- refined our AVHRR Arctic and Antarctic ice surface temperature (IST) retrieval algorithm, including work specific to Greenland,
- developed ATSR retrieval algorithms for the Arctic and Antarctic, including work specific to Greenland,
- investigated the effects of clouds and the atmosphere on passive microwave "surface" temperature retrieval algorithms,
- generated surface temperatures for the Beaufort Sea data set, both from AVHRR and SSM/I,
- continued work on compositing GAC data for coverage of the entire Arctic and Antarctic.

During the second half of the year we will continue along these same lines, and will undertake an detailed validation study of the AVHRR and ATSR retrievals using LEADEx and the Beaufort Sea year-long data. Cloud masking methods used for the AVHRR will be modified for use with the ATSR. Methods of blending in situ and satellite-derived surface temperature data sets will be investigated.

## INTRODUCTION

One essential parameter used in the estimation of radiative and turbulent heat fluxes from satellite data is surface temperature. Sea and land surface temperature (SST and LST) retrieval algorithms that utilize the thermal infrared portion of the spectrum have been developed, with the degree of success dependent primarily upon the variability of the surface and atmospheric characteristics. However, little effort has been directed to the retrieval of the sea ice surface temperature (IST) in the Arctic and Antarctic pack ice or the ice sheet surface temperature over Antarctica and Greenland. The goal of this research is to increase our knowledge of surface temperature patterns and magnitudes in both polar regions, by examining existing data and improving our ability to use satellite data as a monitoring tool. Four instruments are of interest in this study: the AVHRR, ATSR, SMMR, and SSM/I. Our objectives are to

1. Refine the existing AVHRR retrieval algorithm defined in *Key and Haeffliger* (1992; hereafter KH92) and applied elsewhere.
2. Develop a method for IST retrieval from ATSR data similar to the one used for SST. This instrument provides two looks at the same scene and is designed for SST retrieval. Modeling studies analogous to those done with the AVHRR will be done for the ATSR.
3. Further investigate the possibility of estimating surface temperature from passive microwave data (in conjunction with AVHRR clear sky samples) through the use of "effective emissivities" (*Maslanik and Key*, 1993; hereafter MK93) and physical relationships between skin temperature and subsurface temperature. The pilot study described in MK93 needs to be expanded to include other regions and seasons. Error analyses of the uncertainties in atmospheric effects, surface emissivities, and ice concentrations are needed.
4. Use the general method outlined in MK93 to calculate a 12-year record of clear sky equivalent surface temperatures, or possibly all-sky snow-ice interface physical temperatures, from SMMR and SSM/I, compare these temperatures to climatologies, ECMWF modeled surface temperatures, and surface temperatures predicted by a 2-D ice model.
5. Intercompare several ice surface retrieval methods and validate them against ground measurements from the Swiss Camp on the Greenland ice sheet.

Additionally, we intend to develop a surface temperature product based on AVHRR data and possibly blended with drifting buoy and meteorological station temperatures. However, the temporal coverage of this product will depend upon the availability of data from the Pathfinder activity. Discussions are underway with scientists from a number of agencies/institutes to coordinate our activities.

*This document summarizes our progress in the first half of our second project year.*

## 1.0 PROGRESS TO DATE: DATA ACQUISITION

### 1.1 AVHRR Coverage

We are basing all of our AVHRR surface temperature work on the following data sets:

- daily imagery for the Beaufort Sea for June 1992 to July 1993, acquired and processed as part of a separate NASA grant for ice motion studies from AVHRR,
- data acquired during LEADDEX and the SIMMS field experiments,
- two weeks of GAC data during summer and winter of 1984.

We are investigating the possibility of acquiring a multi-year polar GAC subset from the Pathfinder data set at JPL. Due to the computationally intensive nature of this task, we hope to work with NSIDC for low-level processing.

### 1.2 ATSR

ATSR data are being acquired for algorithm validation purposes only. Data continue to be sent to J. Key from Rutherford Appleton Laboratory (England) for times and locations corresponding to recent field experiments. Coverage of one month in four Arctic and one Antarctic locations was originally requested; we now have over seven months of data for each region. Five of the months overlap with the Beaufort Sea AVHRR data set. The figure on the cover of this report gives an example of the ATSR 11  $\mu\text{m}$  channel brightness temperatures of the Beaufort Sea and the North Slope of Alaska.

## 2.0 PROGRESS TO DATE: METHODS

### 2.1 Estimates of IST Using Thermal Data

AVHRR radiance simulations using the LOWTRAN-7 radiative transfer model have been completed using the newly-acquired Arctic and Antarctic radiosonde data and emissivity measurements (Figure 1). The form of the surface temperature predictive equation has changed slightly in order to be more consistent with that used in sea surface temperature retrievals. Sensitivity studies concerning the effects of spring aerosol loading, surface melt, and geographic variations in total precipitable water are in progress. Figure 2 shows the clear sky surface temperature for the Beaufort Sea 1992-93 data set.

Similarly, an algorithm for the ATSR has also been developed using recently acquired response functions. Validation for both the AVHRR and ATSR algorithms is underway with in situ data from LEADDEX and Greenland.

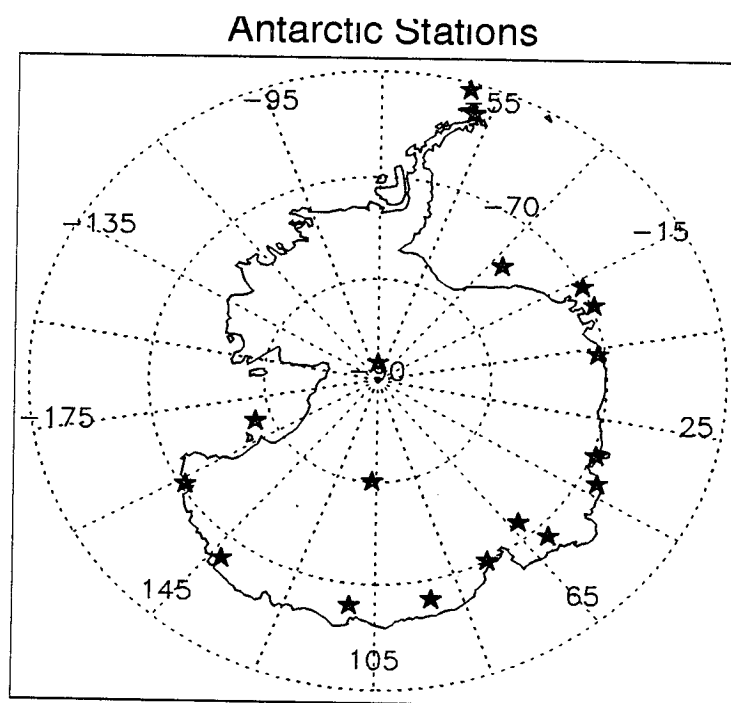
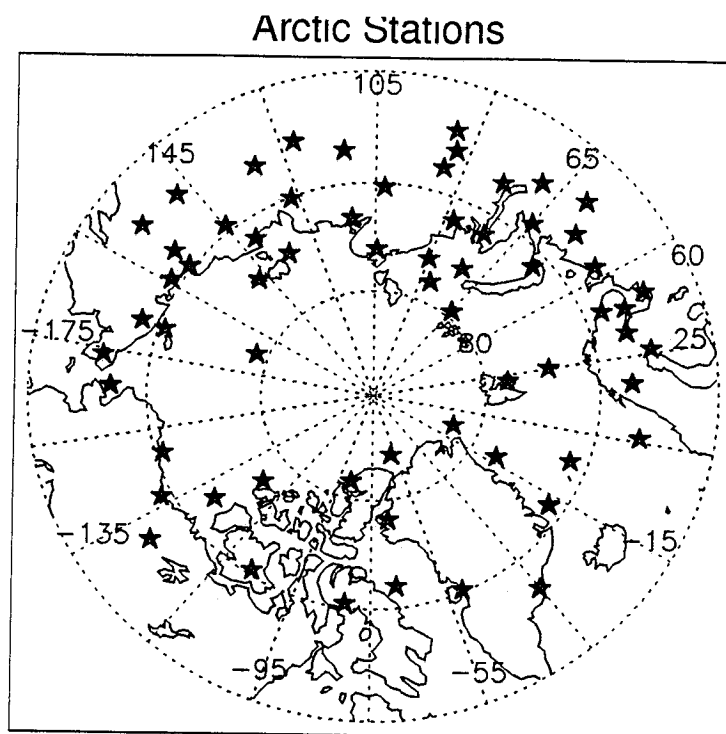


Fig. 1. Arctic and Antarctic stations for which radiosonde data are available.

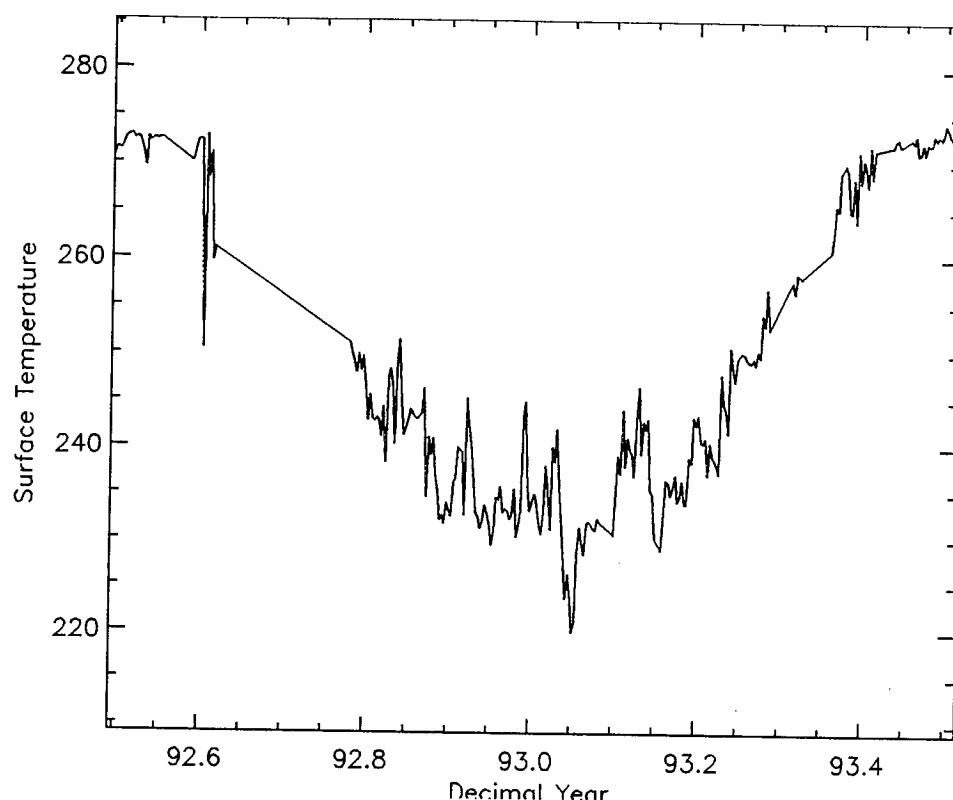


Fig. 2. Clear sky surface temperatures over the Beaufort Sea computed from daily AVHRR LAC data. There is a two month gap from mid-August to mid-October 1992.

Cloud detection in satellite data is the largest obstacle in the path of accurate surface temperature estimation, and is most difficult in the polar regions where surface temperatures and reflectances are often very similar to those of the cloud tops. Two cloud detection methods, the difference between them being the type of input data, have recently been developed and incorporated into the Cloud and Surface Parameter Retrieval (CASPR) system (developed under separate NASA funding). The methods will be modified for use with ATSR data in the near future.

## 2.2 Passive Microwave-Derived Ice Temperatures

Our reasons for considering passive microwave data for IST retrievals are based on three elements of microwave remote sensing. First, since atmospheric water substantially affects retrievals from optical sensors such as AVHRR, microwave data offer the potential for retrieving ISTs under conditions not suited to AVHRR-type sensors. Secondly, data volumes are less, with fields of view comparable to typical mesoscale model resolutions. Finally, since microwave penetration depths vary with frequency, multifrequency passive microwave data can, to some degree, "sound" the snow/ice column to provide physical temperatures at different depths within the ice cover.

Given these properties, our objectives are to: 1) define whether useful IST can be derived from passive microwave imagery; and 2) if warranted, calculate time series of microwave-derived temperatures for comparison to other data sets.

### **2.2.1 Procedure**

From the Stefan-Boltzman relationship, physical temperature  $T = T_B / e$ , where emissivity  $e$  and brightness temperature  $T_B$  are a function of frequency and polarization. Conversion of microwave temperatures to physical temperatures thus requires accurate  $T_B$  measurements and accurate knowledge of surface emissivity. To assess the usefulness of microwave observations for IST retrievals, we are assessing the effects of uncertainties in  $T_B$  and emissivity.

### **2.2.2 Atmospheric Effects**

While microwave emissions penetrate cloud cover and water vapor, the observed top of the atmosphere (TOA) brightness temperatures are not unaffected by atmospheric conditions. Since microwave data could conceivably serve as a substitute for AVHRR when clouds are present, we first consider the effects of atmospheric water on surface temperature retrievals.

Sensitivity studies were carried out using a radiative transfer model (RADTRAN) with different atmospheric conditions for different surface temperatures and different representative ice surfaces. Calculations were performed for 19.35 GHz and 37 GHz, for surface ice temperatures of 230 K, 250 K, and 270 K, and with surface emissivities representing 100% first-year ice, 100% multiyear ice, and mixtures of ice types and open water. Atmospheric water vapor and temperatures were taken from Arctic observations compiled into mean January and July profiles.

The RADTRAN sensitivity studies show that cloud cover can have a significant effect on TOA brightness temperatures ( $T_B$ ), but the effects may not be prohibitive for IST calculations. For example, a uniform, single-layer stratus cloud increases the TOA  $T_B$  at 19 GHz horizontal polarization (19 H) by 5 K for a surface temperature of 230 K and 2 K for a 270 K surface temperature. The effect decreases to 3 K and 0.5 K for vertical polarization. Brightness temperatures increase by about twice this amount at 37 GHz. At the typical emissivities of sea ice, this translates into a nearly equivalent error in IST estimated using a single passive microwave channel. From these calculations, we conclude that single-channel retrievals are capable of yielding surface (penetration depth) temperatures accurate to within 1.5 K using the 19 V channel for typical Arctic winter conditions, and assuming that surface emissivities are known.

### **2.2.3 Effects of Uncertainties in Surface Emissivity**

Given  $IST = T_B / e$ , uncertainty in emissivity  $e$  yields considerable error in IST. For example, since  $e$  at 19 V varies from about 0.95 for first-year ice to 0.80 for multiyear ice, the error introduced by assuming one ice type versus the other is about 15% of the actual sur-

face temperature. Thus, use of microwave data for IST retrievals depends critically on the knowledge of emissivity.

We are investigating three IST algorithms that use different methods of assigning surface emissivities. One approach is to use existing algorithms to estimate the mixtures of ice types. Emissivities are then assigned to each ice type. A second approach is to derive emissivities directly from the microwave data by solving sets of linear equations of independent microwave observations. A third approach is to use IST from other sources (such as clear-sky AVHRR) to estimate microwave emissivities. These emissivities are then used to estimate IST under cloud cover. We plan to test each of these methods. Work to date has focused on the first method, as described below.

First, we describe sensitivity-study tests of this method, which consist of an ice algorithm to determine ice types, followed by specification of emissivities to yield IST from  $T_B$ . This approach is only feasible if ice concentration estimates are independent of surface temperature. This is essentially the case if the NASA Team Algorithm is used, since concentrations are determined using normalized  $T_B$ s (e.g., polarization and gradient ratios). In fact, since penetration depths vary with frequency, the gradient ratio is affected by temperature differences at these depths. The resulting error (which we are testing) is generally assumed to be small.

Typical uncertainties in the Team Algorithm are about 5% for total ice concentration and 20% for ice type. Use of the Team Algorithm thus constrains the surface emissivity assignment, but errors can still be large. For example, in a worst-case situation, an error in ice concentration of 95% first-year ice cover versus 100% ice cover could yield an IST error of about 12 K for an IST of 250 K. This error decreases to about 3 K for a 50% mixture of first-year ice and open water. The error due to multiyear ice uncertainty ranges from about 9 K for a 100% first-year ice cover to about 4 K for a 50% mixture of first-year and multiyear ice.

These errors due to uncertainties in the ice concentration estimates are substantial. However, the errors in the Team Algorithm arise from deviations of the observed brightness temperatures from tie-points supplied to the algorithm. In other words, changes in emissivities from those inherent in the tie-points yield errors in the ice concentration and ice type retrievals. A substantial portion of these deviations in emissivity, particularly in terms of ice type, may be related to atmospheric conditions. From the RADTRAN sensitivity experiments described above, stratus cloud changes the multiyear ice fraction by 20 to 40%.

IST estimates using the Team Algorithm output are therefore affected by errors in ice concentration introduced by emissivity uncertainties, and by errors introduced when inaccurate emissivities are used to convert  $T_B$  to IST. However, errors in the ice retrievals can compensate for errors in the expected emissivities. To visualize this, consider that cloud cover increases observed  $T_B$  more at horizontal polarization than at vertical polarization, and more at higher frequencies than at lower frequencies. Thus, the polarization ratio decreases and the gradient ratio approaches zero (the estimated ice concentration increases and multiyear ice proportion decreases). The overall result, once emissivities are assigned



to the surface, is an increase in apparent emissivity. Since  $IST = T_B / e$ , the increase in  $T_B$  is compensated for by the increase in  $e$ .

To illustrate this, we use RADTRAN results to consider IST estimates when atmospheric effects are introduced. In a typical case, introduction of the stratus cloud increases  $19\text{ V TB}$  by 3 K, increases the estimated total ice concentration by 2%, and reduces the estimated multiyear ice fraction by 18%. When the IST algorithm is applied, the increase in TB is compensated for by the apparent increase in surface emissivity. The resulting error in estimated IST reduced to 1.5 K for a true IST of 230 K. The compensating effects are even greater at a frequency of 37 H. In this case, the observed TB increases by 9 K, but the resulting IST error is less than 1 K. We therefore conclude that IST retrievals may be feasible using this approach.

#### ***2.2.4 Tests of Algorithms on a Time Series***

As a test, we applied the IST algorithm to SSM/I data covering the June 1992-July 1993 time period for the Arctic Ocean and peripheral seas. ISTs were calculated for each day for the complete ocean area using the combination of the NASA Team Algorithm and assigned emissivities. Examination of this time series suggests that estimated ISTs are consistently too high, particularly in summer. For example, Figure 3 shows a time series for a SSM/I 25 km pixel in the Beaufort Sea. Retrieved ISTs vary greatly around the expected value of 273 K during summer. Winter temperature variations are reasonable, but the 19 Ghz temperatures are too high, even if the temperatures represent snow/ice interface temperatures rather than near-surface temperatures. Work is underway to interpret these results, which suggest that the prescribed emissivities in the IST algorithm are not acceptable and that the compensating mechanism noted in the previous section is not sufficient.

#### ***2.2.5 Summary and 1995 Plans***

In summary, the IST approach we have tested so far has the theoretical potential to yield IST estimates accurate to within 1 to 2 K when atmospheric effects are taken into account. Application of this approach to the 1992-1993 time series suggests considerably larger errors, which we have yet to investigate.

We plan to compare the 1992-1993 ISTs to other temperatures to document the apparent biases in the simple IST algorithm used to date. As noted above, our plans are to test two additional IST retrieval methods using the 1992-1993 time series, and to assess the results through comparison with AVHRR-derived ISTs, gridded meteorological data, and individual drifting buoy observations. We plan to carry out similar intercomparisons using aircraft measurements collected this fall over the Beaufort Sea.

We also hope to explore whether an iterative approach that combines ISTs and ice concentration estimates might be used to converge on solutions that improve the estimated ISTs as well as the estimated ice concentrations. As a simple example, when the combination of the Team Algorithm and the IST calculation yield non-realistic ISTs, then one could begin an iterative step by assuming that the ice concentration estimates are in error. Our

plans are to determine whether this approach might prove valuable, particularly when combined with AVHRR- or sounder- derived products that could be used to define skin temperatures and atmospheric conditions.

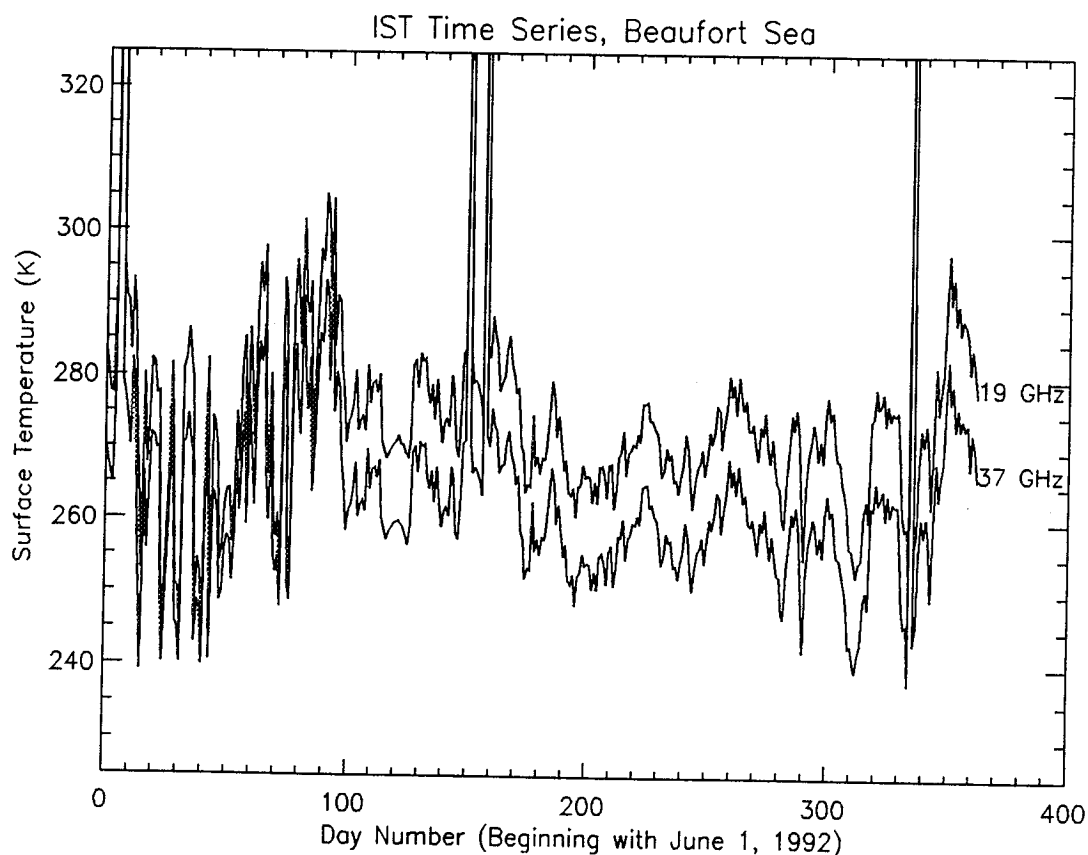


Fig. 3. Time series of SSM/I "surface" (penetration depth) temperature from the Beaufort Sea data set.

### 3.0 PROGRESS TO DATE: PRODUCT GENERATION

#### 3.1 AVHRR-based IST Sampler

Due to unforeseen circumstances regarding AVHRR Pathfinder data acquisition and processing, we are using GAC data currently in-hand for two weeks in 1984 (8/30/84 - 9/13/84 and 2/15/94 - 2/28/94) to develop the multi-level processing procedure that starts with AVHRR Level 1B and ends with a 5-day AVHRR clear sky surface temperature product. We await the delivery of 2-4 months of data from the AVHRR Pathfinder Activity, but are also pursuing other avenues for GAC data acquisition. One possibility is to obtain the data directly from the JPL optical platters and have NSIDC do the subsetting.

Since the low-level processing of these data was not an objective in our original proposal, it is worthwhile to present a breakdown of processing time. The following are the approximate times required for each step in the processing of the Polar GAC data based on the times recorded in the log files for one of the passes.

**TABLE 1. Approximate processing times for the IST GAC sampler.**

Step:	Approximate Time:
1. dd data from tape	4 min
2. Conversion of data to our format	30 sec
3. Checking for missing scanlines	30 sec
4. Extraction of data over the poles into 3 rawfiles	30 sec
5. Fixing the headers of each of the new files	15 sec
6. Extraction of TIP data	1 sec
7. Determination of calibration coefficients	5 sec
8. Calibration of rawfiles	1 min
9. Navigation of data	55 min
10. Compression of data on hard drive	3 min

From these numbers it is clear that the slow link in the chain is the navigation. Any improvement that can be made to speed this step up may mean weeks or months saved in processing time. Now whether or not this can be done is uncertain, but it would definitely be valuable to investigate. Note that the time will probably decrease somewhat in production mode since the processing of this data set involved two navigations, one for channels 1 and 2 and another for the other images.

Figure 4 gives an example of the GAC composites for a 12Z on 31 August 1984. Note that while the target time is 12Z, the composites may actually have data from 6Z to 18Z, depending on the scan angle/time combined decision rule (detailed in the Year 1 Annual Report). When IST retrievals are done with these composites, any time period within this range can be used. For example, we may choose to use only those pixels acquired within one hour of the target time. Of course, the shorter this period is, the fewer the cloud-free pixels, and the longer the compositing time (days) that will be required for reliable statistics..

### 3.2 Year-long Beaufort Sea ISTs

The 1992-93 Beaufort Sea data set, while not in our original plans, has turned out to be a particularly valuable resource. It covers all seasons on a daily basis (albeit with a two month gap) at LAC resolution, is well-calibrated, has co-located SSM/I data, and will eventually have the TOVS data stripped from the data stream and processed into temperature and humidity profiles. In short, there is no other data set like it. It is the test data set for CASPR, with which the surface temperatures shown in Figure 2 were computed. Var-

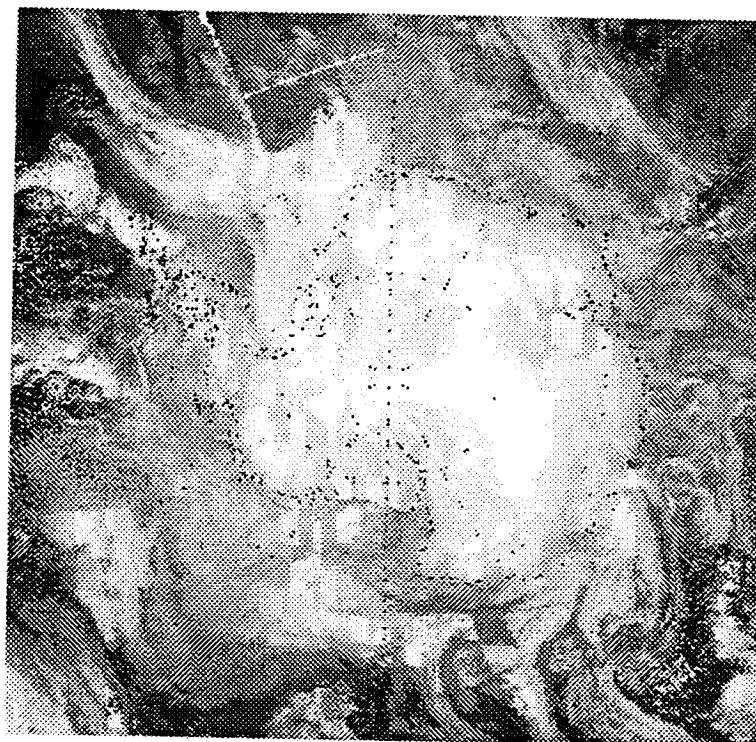
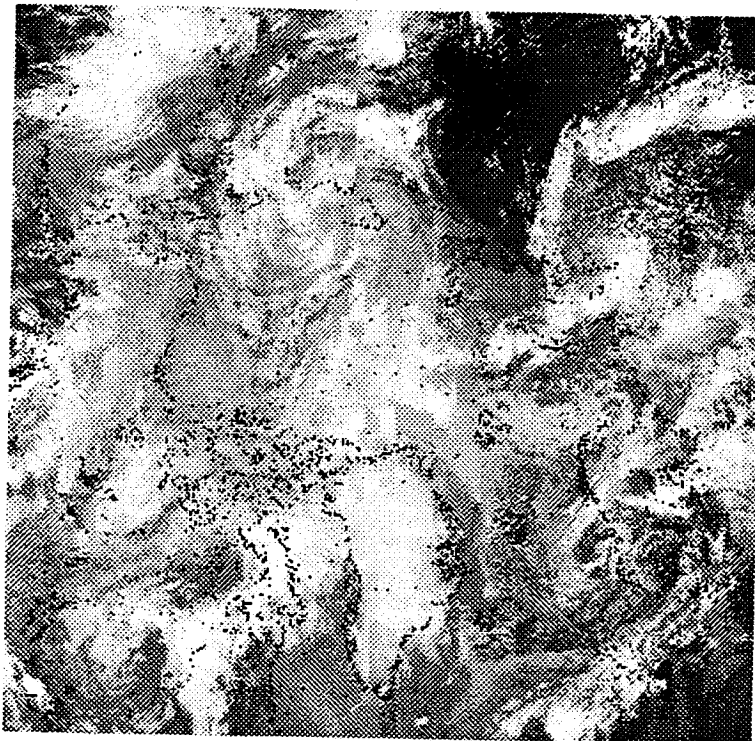


Fig. 4. AVHRR channel 4 brightness temperature composites with a target time of 12Z on 31 August 1984 for the Arctic (top) and Antarctic (bottom).

ious parameters are being retrieved from this data set for the RADARSAT GPS testing, and we will make our temperature products available to the scientific community.

### **3.3 Blended AVHRR-*In Situ* IST Product**

While one of our original objectives was to generate a clear-sky ice surface temperature product from AVHRR data, this goal has been modified somewhat as a result of discussions that took place at the Workshop on Polar Data Sets, Seattle (October 1993). A blended product based on AVHRR clear-sky and drifting buoy temperatures generated considerable interest. Whether or not other data sources can be incorporated - e.g., TOVS or SSM/I - is yet to be determined.

The detailed structure of the blended product is uncertain at present, although it will be similar to the sample AVHRR product discussed previously. Its temporal coverage will depend upon the availability of data (probably from the Pathfinder activity) as well as funding for data processing since this was not part of our original budget.

Seelye Martin of the University of Washington is preparing a surface temperature product for the Arctic based on station and drifting buoy temperatures. We will work with him on blending our two products.

## **4.0 PLANS**

During the second half of the year we will continue along these same lines, and will undertake an detailed validation study of the AVHRR and ATSR retrievals using LEADDEX and the Beaufort Sea year-long data. Cloud masking methods used for the AVHRR will be modified for use with the ATSR. Methods of blending in situ and satellite-derived surface temperature data sets will be investigated.

## **5.0 PUBLICATIONS SUPPORTED IN WHOLE OR IN PART BY THIS GRANT**

Key, J., J.A. Maslanik, T. Papakyriakou, M.C. Serreze, and A.J. Schweiger. On the validation of satellite-derived sea ice surface temperature. *Arctic*, 47(3), 280-287.